

IMPLICATIONS OF WMAP 3 YEAR DATA FOR THE SOURCES OF REIONIZATION

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ABSTRACT

New results on the anisotropy of the cosmic microwave background (CMB) and its polarization based upon the first three years of data from the *Wilkinson Microwave Anisotropy Probe* (WMAP) have revised the electron scattering optical depth downward from $\tau_{\text{es}} = 0.17^{+0.08}_{-0.07}$ to $\tau_{\text{es}} = 0.09 \pm 0.03$. This implies a shift of the effective reionization redshift from $z_r \simeq 17$ to $z_r \simeq 11$. Previous attempts to explain the high redshift of reionization inferred from the WMAP 1-year data have led to widespread speculation that the sources of reionization must have been much more efficient than those associated with the star formation observed at low redshift. This is consistent, for example, with the suggestion that early star formation involved massive, Pop III stars which early-on produced most of the ionizing radiation escaping from halos. It is, therefore, tempting to interpret the new WMAP results as implying that we can now relax those previous high demands on the efficiency of the sources of reionization and perhaps even turn the argument around as evidence *against* such high efficiency. We show that this is not the case, however. The new WMAP results also find that the primordial density fluctuation power spectrum has a lower amplitude, σ_8 , and departs substantially from the scale-invariant spectrum. We show that these effects combine to cancel the impact of the later reionization implied by the new value of τ_{es} on the required ionizing efficiency per collapsed baryon. The delay of reionization is surprisingly well-matched by a comparable delay (by a factor of ~ 1.4 in scale factor) in the formation of the halos responsible for reionization.

Subject headings: cosmic microwave background – cosmology: theory – diffuse radiation – galaxies: formation – intergalactic medium

1. INTRODUCTION

One of the most important outstanding problems in cosmological structure formation is how and when the universe was reionized. Observational constraints such as the Thomson scattering optical depth to the last scattering surface (Kogut et al. 2003; Page et al. 2006) from the large-angle polarization anisotropy in the CMB detected by WMAP and the intergalactic, hydrogen Ly α absorption spectra of high-redshift quasars (e.g., Becker et al. 2001) provide crucial constraints on the theory of cosmic reionization and the structure formation which caused it during the early epochs that have thus far escaped direct observation. The WMAP first-year data implied an electron scattering optical depth, $\tau_{\text{es}} = 0.17$, which seemed surprisingly large at the time, since it was well in excess of the value, $\tau_{\text{es}} \simeq 0.04$, for an intergalactic medium (IGM) abruptly ionized at $z_r \simeq 6.5$, the reionization epoch which had been suggested by quasar measurements of the Gunn-Peterson (Gunn & Peterson 1965; “GP”) effect. In order for such an abrupt reionization to explain the high value of 0.17 observed by WMAP for τ_{es} , in fact, $z_r \simeq 17$ is required. This presented a puzzle for the theory of reionization: How was reionization so advanced, so *early* in our observed Λ CDM universe, and yet so *extended* in time as to accumulate the high τ_{es} observed by WMAP, while *ending* as late as $z \simeq 6.5$ to satisfy the quasar spectral constraints?

This stimulated widespread speculation regarding the efficiency for the formation of the early stars and/or miniquasars which were the sources of reionization, as well as for the escape of their ionizing photons into the IGM (e.g., Haiman & Holder 2003; Cen 2003; Wyithe & Loeb 2003; Kapling-

hat et al. 2003; Sokasian et al. 2004; Ciardi, Ferrara, & White 2003; Ricotti & Ostriker 2004). A general consensus emerged that the efficiencies for photon production and escape associated with present-day star formation were not adequate to explain the early reionization implied by the high τ_{es} value, given the rate of early structure formation expected in the Λ CDM universe. Common to most attempts to explain the high τ_{es} was the assumption that early star formation favored massive Population III stars, either in “minihalos,” with virial temperatures $T_{\text{vir}} < 10^4$ K, requiring that H_2 molecules cool the gas to enable star formation (Abel, Bryan, & Norman 2002; Bromm, Coppi, & Larson 2002), or else in larger halos with $T_{\text{vir}} > 10^4$ K, for which atomic hydrogen cooling is possible, instead. A high efficiency for turning halo baryons into stars and a high escape fraction for the ionizing radiation into the IGM were generally required as well. Several effects were suggested that could extend the reionization epoch, too, including the rising impact of small-scale structure as a sink of ionizing photons (e.g., Shapiro, Iliev, & Raga 2004; Iliev, Shapiro, & Raga 2005; Iliev, Scannapieco, & Shapiro 2005), the suppression of low-mass source-halo formation inside the growing intergalactic H II regions (e.g., Haiman & Holder 2003), and a general decline of the efficiency for releasing ionizing radiation over time (e.g., Cen 2003; Choudhury & Ferrara 2005).

With three years of polarization data, WMAP (henceforth, “WMAP3”), has now produced a more accurate determination of τ_{es} , which revises the optical depth downward to $\tau_{\text{es}} = 0.09 \pm 0.03$ (Page et al. 2006). This value is consistent with an abrupt reionization at $z_r = 11$, significantly later than that implied by the WMAP first-year data (henceforth, “WMAP1”). It is natural to wonder if this implies that the high efficiency demanded of ionizing photon production by WMAP1, described above, can now be reduced, accordingly, to accommodate the later epoch of reionization determined by

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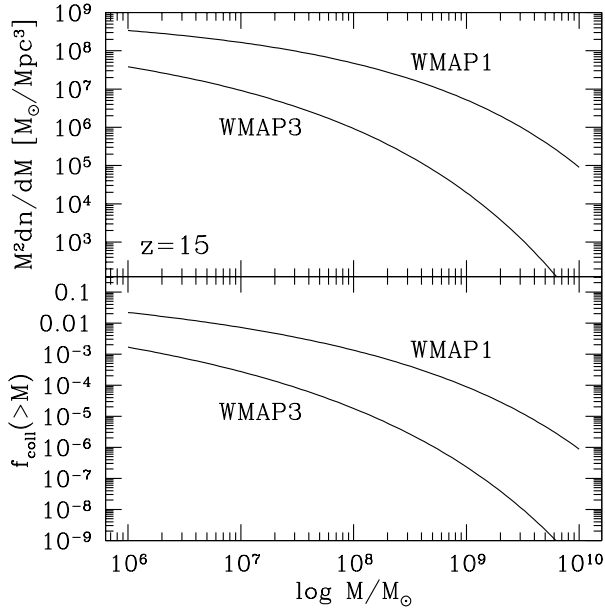


FIG. 1.— Halo abundance vs. mass for new (WMAP3) and old (WMAP1) parameters at $z = 15$, as labelled. *Top*: Press-Schechter mass function. *Bottom*: Fraction of matter $f_{\text{coll}}(>M)$ in halos with mass greater than M .

WMAP3. In what follows, we will show that this is not the case.

Structure formation in the Λ CDM universe with the primordial density fluctuation power spectrum measured by WMAP3 is delayed relative to that in the WMAP1 universe, especially on the small-scales responsible for the sources of reionization. This, by itself, is not surprising, since there was always a degeneracy inherent in measuring the amplitude of the primordial density fluctuations using the CMB temperature anisotropy alone, resulting from the unknown value of τ_{es} . Higher values of τ_{es} , that is, imply higher amplitude density fluctuations to produce the same level of CMB anisotropy. This degeneracy is broken by the independent measurement of τ_{es} made possible by detecting the polarization anisotropy, as well. Hence, when WMAP3 revised the value of τ_{es} downward relative to WMAP1, so it revised downward the amplitude of the density fluctuations. This same decrease of τ_{es} implies a tilt away from the scale-invariant power spectrum, $P(k) \propto k^{n_s}$ with $n_s = 1$, which lowers the density fluctuation amplitude on small scales more than on large scales. As we will show, this delays the structure formation which controls reionization by just the right amount such that, if reionization efficiencies were large enough to make reionization early and $\tau_{\text{es}} = 0.17$ in the WMAP1 universe, the same efficiencies will cause reionization to be later in the WMAP3 universe and $\tau_{\text{es}} \sim 0.09$, as required.

In §2, we compare the rate of structure formation in Λ CDM according to WMAP1 and WMAP3, on the scales relevant to reionization. In §3, we relate the history of reionization to the growth of the mass fraction collapsed into source halos, and use this to compare the reionization histories in WMAP3 and WMAP1 universes. Our conclusions are summarized in §4.

We adopt cosmological parameters $(\Omega_m h^2, \Omega_b h^2, h, n_s, \sigma_8) = (0.14, 0.024, 0.72, 0.99, 0.9)$ (Spergel et al. 2003) and $(0.127, 0.022, 0.73, 0.95, 0.74)$ (Spergel et al. 2006) for WMAP1 and WMAP3, respectively. The most notable changes from old to new are: a reduction of normalization of the power spectrum on large scales ($\sigma_8 = 0.9 \rightarrow 0.74$) and more “tilt” ($n_s = 0.99 \rightarrow 0.95$). Throughout this paper, we use

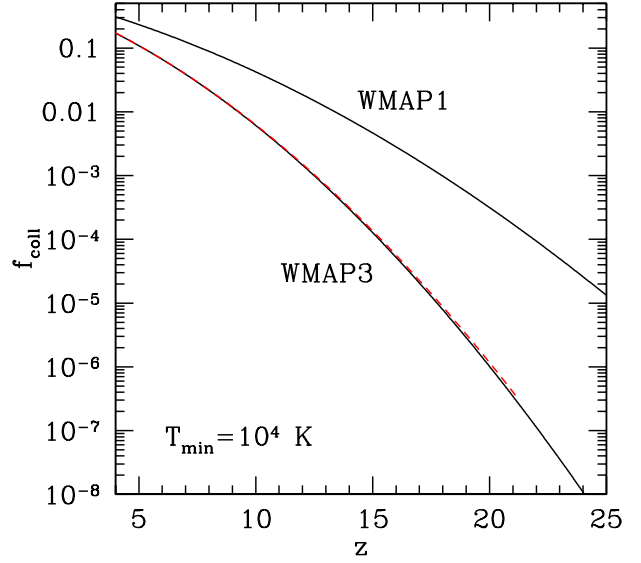


FIG. 2.— Collapsed fraction vs. redshift for halos with virial temperatures greater than $T_{\text{min}} = 10^4$ K, for WMAP1 and WMAP3, as labelled. Dashed curve, nearly on top of “WMAP3” curve, is “WMAP1” curve with $1+z \rightarrow (1+z)/1.4$.

the transfer function of Eisenstein & Hu (1999).

2. STRUCTURE FORMATION AT HIGH REDSHIFT

A fundamental building block of models of reionization is the fraction of the mass contained in virialized halos – the “collapsed fraction” – the sites of ionizing photon production and release. Using the Press-Schechter formalism (Press & Schechter 1974), this collapsed fraction is given by:

$$f_{\text{coll}}(z) = \text{erfc} \left[\nu_{\text{min}}(z) / \sqrt{2} \right], \quad (1)$$

where $\nu_{\text{min}}(z) \equiv \delta_c / [D(z)\sigma(M_{\text{min}})]$, $\sigma^2(M)$ is the variance in the present-day matter density field according to linear perturbation theory, as filtered on the mass scale M , $D(z)$ is the linear growth factor ($D(z) \propto 1/(1+z)$ and $\delta_c = 1.686$ in the matter-dominated era), and $M_{\text{min}}(z)$ is the minimum mass for collapsed objects. For studies of reionization, the minimum mass is typically parameterized in terms of the minimum virial temperature, T_{min} , of halos capable of hosting ionizing sources, $M_{\text{min}} \simeq 4 \times 10^7 M_{\odot} [(T_{\text{min}}/10^4 \text{ K})(10/(1+z))(1.22/\mu)]^{3/2}$, where $\mu = 1.22$ for fully neutral gas (Iliev & Shapiro 2001).

For Λ CDM, $\sigma(M)$ for $M \sim 10^6 - 10^8 M_{\odot}$ is lower for WMAP3 than for WMAP1 by about 30 percent. During reionization, when such halos are still rare, we expect their abundance to be exponentially suppressed by this factor. This is clearly shown in Figure 1, where the new halo abundance and collapsed fraction are lower than the old ones by 1-2 orders of magnitude. Since the threshold for halo collapse scales at these redshifts as $\delta_c/D(z) \propto 1+z$, structure formation on these mass scales is delayed by a factor $1/0.7 \sim 1.4$ in scale factor. This is illustrated in Figure 2, where we plot $f_{\text{coll}}(T > T_{\text{min}} = 10^4 \text{ K})$ versus redshift and show that the shift of 1.4 in scale factor provides an excellent description of the delay in structure formation which results.

For the simplest possible reionization model, in which the universe is instantly and fully ionized at some redshift z_r , the optical depth $\tau_{\text{es}} \propto (1+z_r)^{3/2}$. If we assume that $f_{\text{coll}}(z_r)$ is a constant, so that reionization occurs when the collapsed fraction reaches some threshold value, then our simple estimate

implies that the change in the cosmological parameters alone reduces τ_{es} by a factor of $1.4^{3/2} = 1.65$, from $\tau_{\text{es}} \sim 0.17$ to $\tau_{\text{es}} \sim 0.1$. In the next section we discuss the motivation behind tying the reionization history to the collapsed fraction.

3. REIONIZATION HISTORY

An important quantity in the theory of cosmic reionization is the number of ionizing photons per hydrogen atom in the universe required to complete reionization³. In the absence of recombinations, this ratio is unity. Given some observational constraint on the epoch of reionization, such as the onset of the GP effect at $z \simeq 6.5$, we can deduce that at least one ionizing photon per atom had to have been released by that time. This ratio can then be used to predict other quantities, such as the associated metal enrichment of the universe (e.g., Shapiro, Giroux, & Babul 1994) or the intensity of the near infrared background (e.g., Santos, Bromm, & Kamionkowski 2002; Fernandez & Komatsu 2006). Most models of cosmic reionization link the ionized fraction of the IGM to the fraction of matter in collapsed objects capable of hosting stars (e.g., Shapiro, Giroux, & Babul 1994; Chiu & Ostriker 2000; Wyithe & Loeb 2003; Haiman & Holder 2003; Furlanetto, Zaldarriaga, & Hernquist 2004; Iliev et al. 2005; Alvarez et al. 2006). For a given model, reionization is complete whenever the total number of ionizing photons emitted per hydrogen atom reaches some threshold value. Along with the escape fraction, star formation efficiency, and stellar initial mass function, the evolution of the collapsed fraction $f_{\text{coll}}(z)$ forms the basis for calculation of this ratio and thus the reionization history.

To relate τ_{es} to the halo abundance encoded in f_{coll} , it is necessary to determine the relationship between the reionization history and the collapsed fraction. If we assume every H atom which ends up in a collapsed halo releases on average $f_\gamma(z)$ ionizing photons, and that $\epsilon_\gamma(z)$ is the number of ionizing photons consumed per ionized H atom, then we can write a simple relation between f_{coll} and the mean ionized fraction,

$$x_e(z) = \frac{f_\gamma(z)}{\epsilon_\gamma(z)} f_{\text{coll}}(z) \equiv \zeta(z) f_{\text{coll}}(z) \quad (2)$$

(e.g., Furlanetto, Zaldarriaga, & Hernquist 2004). For simplicity, we will assume a constant value, $\zeta(z) = \zeta_0$ (this simplification does not affect our main conclusions), and fix the value of ζ_0 for a given T_{min} , so that $\tau_{\text{es}} = 0.17$ for WMAP1. Reionization is complete when the collapsed fraction reaches a threshold given by $f_{\text{coll}}(z_r)\zeta_0 = 1$.

In Figure 3, we plot the value of ν_{min} which corresponds to $T_{\text{min}} = 10^4$ K. As mentioned in §2, WMAP3 implies a delay of structure formation by ~ 1.4 in scale factor. In the lower panel, we compare the reionization histories for WMAP1 and WMAP3 according to equation (2), for the same efficiency ζ_0 . The same shift by a factor 1.4 in scale factor is also present in the reionization histories, which is not surprising, since we have assumed that $x_e \propto f_{\text{coll}}$, and f_{coll} is a unique function of ν_{min} . As mentioned in §2, this change can account for a shift in the implied value of τ_{es} from 0.17 to 0.1, quite close to the WMAP3 value of 0.09 ± 0.03 . On the basis of this simple calculation, we conclude that the reduction of τ_{es} from WMAP1 to WMAP3 does not, itself, significantly reduce the demand for high efficiency of ionizing sources imposed previously by WMAP1.

³ For simplicity, we will neglect helium reionization. This does not effect our basic conclusions here.

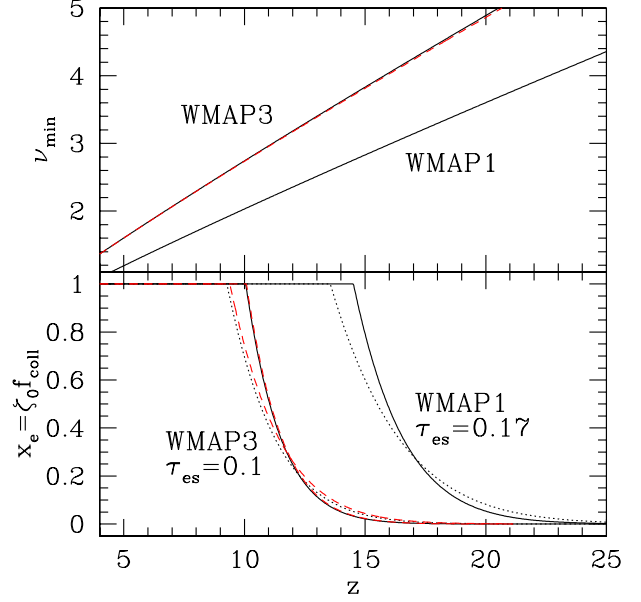


FIG. 3.— Evolution with redshift for WMAP1 and WMAP3, as labelled. *Top*: Threshold for collapse, ν_{min} , for a halo with virial temperature 10^4 K. Dashed curve, nearly on top of “WMAP3” curve, is “WMAP1” curve with $1+z \rightarrow (1+z)/1.4$. *Bottom*: Reionization histories given by $x_e = \zeta_0 f_{\text{coll}}$, labelled by the corresponding values of τ_{es} , for $\zeta_0 = 170$ and $T_{\text{min}} = 10^4$ K (solid), and $\zeta_0 = 35$ and $T_{\text{min}} = 2 \times 10^3$ K (dotted). The two dashed curves are “WMAP1” curves with $1+z \rightarrow (1+z)/1.4$.

3.1. Effect of recombinations

Recombinations undoubtedly play an important role during reionization. To first approximation, they should determine by what amount the parameter $\epsilon_\gamma(z)$ appearing in equation (2) exceeds unity. The quantity $\epsilon_\gamma - 1$ is equal to the average number of recombinations that all ionized atoms must undergo during reionization, N_{rec} . As shown by Iliev et al. (2005), $N_{\text{rec}} \simeq 0.6$ at percolation for large scale simulations of reionization that resolve all sources with masses greater than $\approx 2 \times 10^9 M_\odot$, but do not resolve clumping of the IGM on scales smaller than ≈ 700 comoving kpc. Surely, smaller scale structure affects reionization strongly (e.g., Iliev, Shapiro, & Raga 2005; Iliev, Scannapieco, & Shapiro 2005), and therefore the number of recombinations per ionized atom is likely to be higher. For example, Alvarez, Bromm, & Shapiro (2006) found that the recombination time in the gas ionized by the end of the lifetime of a $100 M_\odot$ star embedded in a $10^6 M_\odot$ halo at $z = 20$ is ~ 20 Myr, roughly one tenth of the age of the universe at that time.

At the high redshifts considered here, the ratio of the age of the universe to the recombination time is proportional to $(1+z)^{3/2}$. Since structure formation is later for WMAP3 than for WMAP1 by a factor of 1.4 in scale factor, photon consumption due to recombinations is lower for WMAP3 by a factor $\sim 1.4^{3/2} = 1.65$. Even if recombinations dominate the consumption of ionizing photons during reionization, therefore, the new WMAP data require an efficiency ζ_0 which is at most a factor of only ~ 1.65 lower than that for the first year data. This is true even if clumping increases toward lower redshift, since the evolution of clumping follows structure formation and is, therefore, similarly delayed.

4. DISCUSSION

We have shown that the new cosmological parameters reported for WMAP3 imply that structure formation at high redshift on the scale of the sources responsible for reionization was delayed relative to that implied by WMAP1. This delay can account for the new value in τ_{es} without substantially changing the efficiency with which halos form stars. Recombinations are fewer when reionization is later, but the reduction is modest. Even the IGM clumping factor on which this recombination correction depends follows the delay in structure formation.

An important additional constraint on reionization is that it end at a redshift $z \gtrsim 6.5$, in order to explain the lack of a GP trough in the spectra of quasars at $z \lesssim 6.5$. Because the GP trough saturates at a very small neutral fraction, the quasar data alone do not tell us when the universe became mostly ionized. Indeed, it is possible for the ionized fraction to have been quite high already at high redshift $z \sim 10$ while there remained a neutral fraction sufficiently high to satisfy the GP constraint at $z \sim 6.5$ (e.g., Choudhury & Ferrara 2006). While the universe may become mostly ionized well before $z \sim 6.5$, it cannot be later than this, however. Because of the shifting in time of structure formation we have described, any model of reionization which previously satisfied the WMAP1 $\tau_{\text{es}} \sim 0.17$ constraint *and* became mostly ionized at $z \lesssim 9$ would now reionize too late to be compatible with the quasar observations. Recently, Haiman & Bryan (2006) used this fact to deduce that the formation of massive Pop III stars was suppressed in minihalos.

While $\sigma_8 = 0.744$ and $n_s = 0.951$ are the most likely values obtained from the new WMAP data alone, there remain sig-

nificant uncertainties. When combined with other data sets such as large-scale structure (e.g., Spergel et al. 2006) and the Lyman- α forest (e.g., Viel, Haehnelt, & Lewis 2006; Seljak, Slosar, & McDonald 2006), important differences arise. While these differences may seem small from the point of view of the statistical error of the observational data, the implications for reionization can be quite dramatic, as we have seen here. It is also important to note that these measurements of the power spectrum are on scales much larger than those relevant to the sources of reionization. As such, the theory of reionization requires us to extrapolate the power spectrum by orders of magnitude beyond where it is currently measured. This means that the study of reionization is crucial to extending the observational constraints on the origin of primordial density fluctuations (e.g., by inflation) over the widest range of wavenumbers accessible to measurement. Direct observations of the high redshift universe such as 21-cm tomography (e.g., Iliev et al. 2002; Zaldarriaga, Furlanetto, & Hernquist 2004; Shapiro et al. 2006; Mellema et al. 2006) and large-aperture infrared telescopes such as JWST promise to diminish the uncertainties which currently prevent us from making reliable statements about the nature of the first sources of ionizing radiation.

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REFERENCES

- Abel, T., Bryan, G. L., & Norman, M. L. 2002, *Science*, 295, 93
 Alvarez, M. A., Bromm, V., & Shapiro, P. R. 2006, *ApJ*, 639, 621
 Alvarez, M. A., Komatsu, E., Doré, O., & Shapiro, P. R. 2006, *ApJ*, in press, astro-ph/0512010
 Becker, R. H., et al. 2001, *AJ*, 122, 2850
 Bromm, V., Coppi, P., & Larson, R. B. 2002, *ApJ*, 564, 23
 Cen, R. 2003, *ApJ*, 591, 12
 Choudhury, T. R., & Ferrara, A. 2005, *MNRAS*, 361, 577
 Choudhury, T. R., & Ferrara, A. 2006, *MNRAS*, submitted, astro-ph/0603617
 Ciardi, B., Ferrara, A., & White, S. D. M. 2003, *MNRAS*, 344, 7
 Chiu, W. A., & Ostriker, J. P. 2000, *ApJ*, 534, 507
 Eisenstein, D. J., & Hu, W. 1999, *ApJ*, 511, 5
 Fernandez, E. R., & Komatsu, E. 2005, *ApJ*, submitted (astro-ph/0508174)
 Furlanetto, S. R., Zaldarriaga, M., & Hernquist, L. 2004, *ApJ*, 613, 1
 Gunn, J. E., & Peterson, B. A. 1965, *ApJ*, 142, 1633
 Haiman, Z., & Bryan, G. L. 2006, *ApJ*, submitted, astro-ph/0603541
 Haiman, Z., & Holder, G. P. 2003, *ApJ*, 595, 1
 Iliev, I. T., & Shapiro, P. R. 2001, *MNRAS*, 325, 468
 Iliev, I. T., Shapiro, P. R., Ferrara, A., & Martel, H. 2002, *ApJ*, 527, L123
MNRAS, 341, 811
 Iliev, I. T., Shapiro, P. R., & Raga, A. C. 2005, *MNRAS*, 361, 405
 Iliev, I. T., Scannapieco, E., & Shapiro 2005, *ApJ*, 624, 491
 Iliev, I. T., Mellema, G., Pen, U., Merz, H., Shapiro, P. R., Alvarez, M. A. 2005, *MNRAS*, submitted, astro-ph/0512187
 Kaplinghat, M., Chu, M., Haiman, Z., Holder, G. P., Knox, L., & Skordis, C. 2003, *ApJ*, 583, 24
 Kogut, A., et al. 2003, *ApJS*, 148, 161
 Mellema, G., Iliev, I. T., Pen, U. L. & Shapiro, P. R. 2006, *MNRAS*, submitted (astro-ph/0603518)
 Page et al. 2006, *ApJ*, submitted, astro-ph/0603450
 Press, W. H., & Schechter, P. 1974, *ApJ*, 187, 425
 Ricotti, M. & Ostriker, J. P. 2004, *MNRAS*, 350, 539
 Santos, M. R., Bromm, V., & Kamionkowski, M. 2002, *MNRAS*, 336, 1082
 Seljak, U., Slosar, A., & McDonald, P. 2006, astro-ph/0604335
 Shapiro, P. R., Giroux, M. L., & Babul, A. 1994, *ApJ*, 427, 5
 Shapiro, P. R., Iliev, I. T., & Raga, A. C. 2004, *MNRAS*, 348, 753
 Shapiro, P. R., Ahn, K., Alvarez, M. A., Iliev, I. T., Martel, H., & Ryu, D. 2006, *ApJ*, in press, astro-ph/0512516
 Sokasian, A., Yoshida, N., Abel, T., Hernquist, L., & Springel, V. 2004, *MNRAS*, 350, 47
 Spergel, D. N. et al. 2003, *ApJS*, 148, 175
 Spergel, D. N. et al. 2006, *ApJ*, submitted, astro-ph/0603449
 Viel, M., Haehnelt, M. G., & Lewis, A. 2006, *MNRAS*, submitted, astro-ph/0604310
 Wyithe, J. S. B., & Loeb, A. 2003, *ApJ*, 588, L69
 Zaldarriaga, M., Furlanetto, S. R., & Hernquist, L. 2004, *ApJ*, 608, 622